Degenerate Quantum Gases 2008

lecture 1

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Lecturer

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- Reception (preferably) Wed 12-14.

Course info

- Course web page: http://theory.physics.helsinki.fi/~quantumgas/
- 3sw or 5sp
- Exercises (roughly) every second week and they give 25% of the grade.
- No special exercise session, I will go over the exercises during the lectures.
- Return the exercises before $16:00$ on thursday before the lecture on friday.
- Final exam

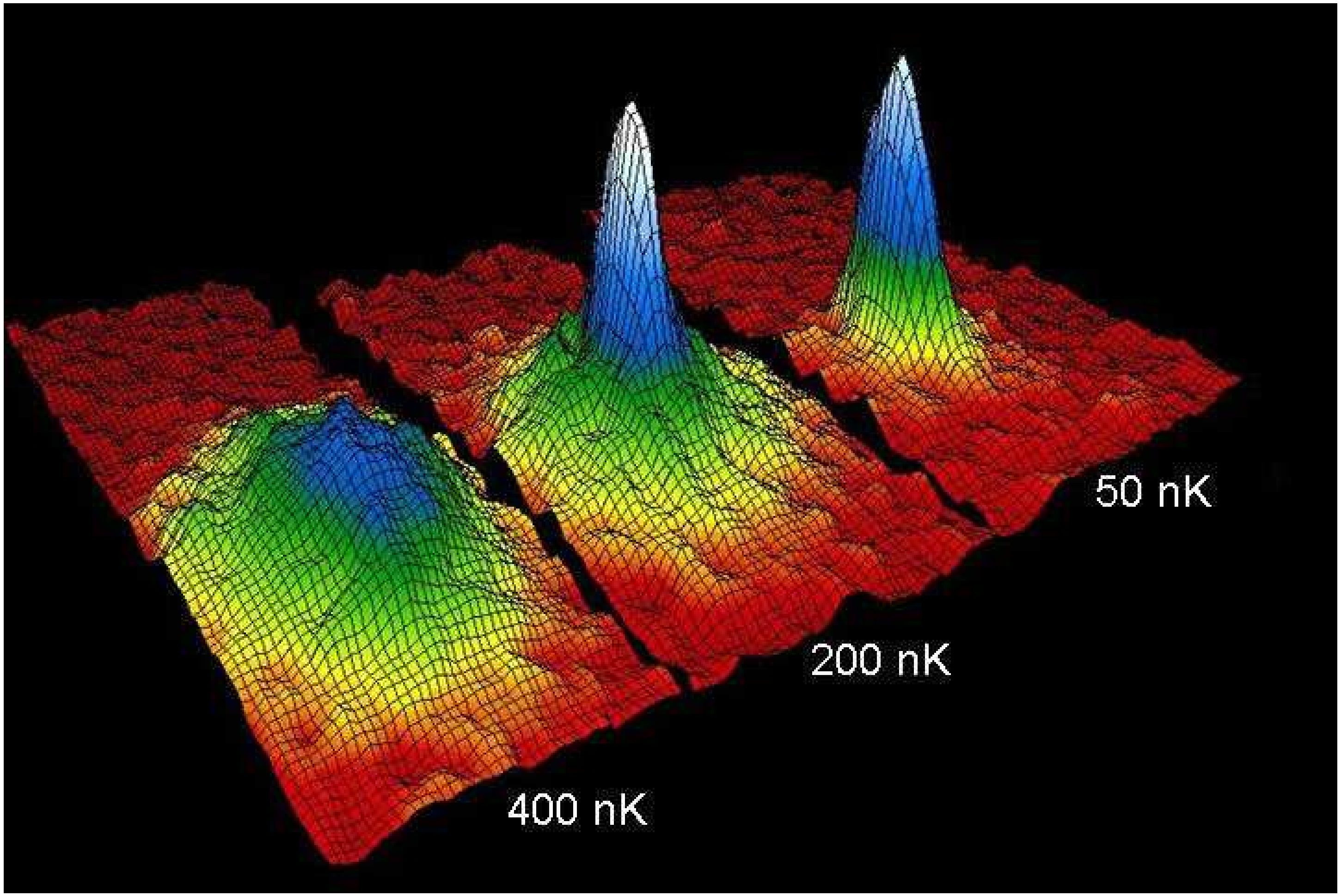
Suggested material (for example)...

- book by C.J. Pethick and H. Smith: “Bose-Einstein condensation in dilute gases”, CUP 2002
- Theory oriented review article F. Dalfovo, S. Giorgini, L. P. Pitaevskii, and S. Stringari: “Theory of Bose-Einstein condensation in trapped gases”, Review of Modern Physics 71, 463-512 (1999)
- Experimentally oriented review article W. Ketterle, D.S. Durfee, D.M. Stamper-Kurn: “Making, probing and understanding Bose-Einstein condensates”, cond-mat/9904034 (from http://xxx.lanl.gov)

Suggested material (...continued)

- Review article on vortices Alexander Fetter and Anatoly Svidzinsky: “Vortices in a trapped dilute Bose-Einstein condensate”,cond-mat/0102003
- On trapping and laser cooling book by H. J. Metcalf and P. van der Straten: ‘”Laser Cooling and Trapping”
- the Nobel lectures on laser cooling by Chu, Phillips and Cohen-Tannoudji are easy to read and informative, Reviews of Modern Physics **70** issue 3, 1998 http://rmp.aps.org/
- the Nobel lectures by Wieman, Cornell, and Ketterle on the BEC provide some nice background: Rev. Mod. Phys. **74**, 2002.
- others....

We are going to learn about this....



Contents of this course

- Bose-Einstein condensation of an ideal gas
- Laser cooling of atoms
- Trapping of neutral atoms
- Two-body interactions between cold atoms
- Microscopic and meanfield theory
- Static and dynamic properties of a condensate
- Condensates and superfluidity
- Matter wave interference and atom lasers
- Rotating condensates and vortices

Contents continue...

- Mixtures and vectorial condensates
- Beoynd the mean field theory and $T \neq 0$
- Optical lattices
- Dimensional cross-overs
- Cold fermions and BCS theory
- Feshbach resonance and the BCS-BEC cross-over

Brief history of BEC

Already in 1925 Bose and Einstein discussed condensation for ideal bosons

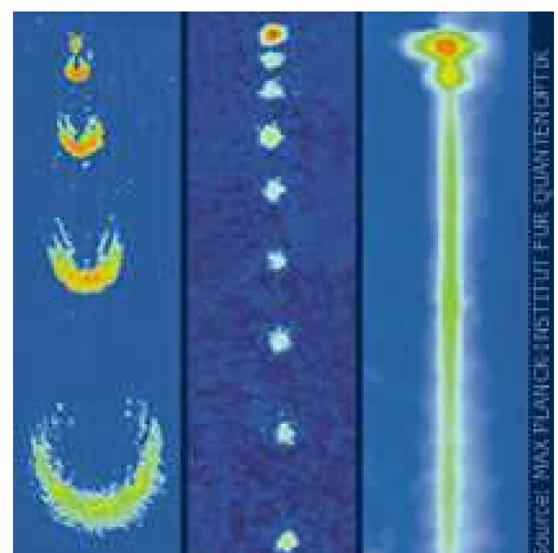
- Quantum statistical phase transition
- Plays a role in explaining the properties of superfluid Helium (however, interaction are strong)
- Laser has a “high occupation” of a single mode (photon number is not a well defined concept...lasing is a non-equilibrium process)
- Superconductors as “condensates” of Cooper-pairs

More history....

- Mercury superconductor by Onnes 1911
- Superfluid Helium (Liquid He 1908, no measurable resistance to flow through small capillaries 1938)
- Theoretical understanding came later (London 1938 suggested a connection with BEC)
- Superfluidity in $^3\mathrm{He}$ (Osheroff 1971)
- All these are strongly interacting and the condensate fraction can be much less than 1... a BEC from a dilute (gas) sample desirable...

Nobel 2001

- Quest to achive (almost) pure condensate of atoms took decades
- At low temperatures atoms form solids... find a way around this
- Finally the experimental realization in 1995 (Nobel 2001: Cornell, Wieman, and Ketterle) using laser cooling and evaporation



1. Why are condensates interesting?

- High condensate fractions, almost $100\,\%$.
- Weakly interacting... microscopic theory for this many-body system of millions of atoms doable.
- superfluidity
- Easy to tune...additional complexity can be added little by little
- wavefunction can be “seen” optically... an appealing way to study quantum dynamics
- precision measurements: gravity, rotation sensors, and time measurements
- atom optics and quest towards quantum computing

2. Why are condensates interesting?

- Very recently... BEC-BCS cross-over: from the condensate into a traditional BCS states of a superconductor
- Mixtures are possible...
- Realize condensed matter models...
- Possibility of monitoring the phase transitions (spontaneous symmetry breaking) in real time!
- see demo movie...

BEC=condensate of composite bosons

- Condensate of atoms is a condensate of a bound system of fermions (?)
- $neutrons + protons + electrons = neutrons + 2 \times atomic\ number$
- Isotopes with ODD atomic mass have EVEN spin...composite bosons
- Consider composite bosons as point like particles
- This makes sense when temperature is much lower than the energy of internal exitations
- This is always valid for us...
- Use alkali atoms: Rb, Na, Li, K (available lasers and atomic collisional properties)

Introduction: some typical numbers

- very dilute gases $n \sim 10^{13} - 10^{14}\,1/\mathrm{cm}^3$ i.e. interatomic spacing of order $0.2\,\mu\mathrm{m}$
- compare: air density $\sim 10^{19}\,1/\mathrm{cm}^3$ and solids have densities in the neighborhood of $10^{22}\,1/\mathrm{cm}^3$.
- Temperature $1\ldots 100\,\mathrm{nK}$ (lowest ever)
- number of atoms typically $10^4 \ldots 10^7$
- Trap frequency (perhaps) $\omega \sim 2\pi \cdot 100\,\mathrm{Hz}$ and oscillator length $l = \sqrt{\hbar/m\omega} \sim 1\,\mu\mathrm{m}$ (BEC roughly cell sized...)
- Prepare the condensate in about a 60 seconds
- Do something with the condensate for ~ 10 seconds

Temperature scale...

- At temperature T: $K_x = m\langle v_x^2\rangle/2 = k_B T/2$
- de Broglie wavelength λ of a particle is related to its momentum through the formula $2\pi\hbar/\lambda = mv$
- If we take the characteristic velocity $v^2 \sim k_B T/m$ and fix some constants...
- we find the so-called thermal de Broglie wavelength $\lambda_T = \sqrt{\frac{2\pi\hbar^2}{mk_B T}}$.
- Many-body quantum effects become "large" when the interatomic spacing $l \sim 1/n^{1/3}$ becomes shorter than λ_T (phase-space density > 1)
- **temperatures around** $T \sim 1\,\mu\mathrm{K}$ with relevant densities for dilute BEC:s

Typical experimental setup

- You need an ultra-high-vacuum chamber.
- Find the atoms of appropriate isotope to work with. A beam of these atoms are extracted from on oven.
- The atoms flying out from the have temperature of several hundreds of Kelvins. They are too fast to be trapped in the so-called magneto-optical trap i.e. MOT. Therefore, one shines a laser beam of appropriate frequency against the beam. The radiation pressure then cools the atoms to some tens of Kelvins. To make this pre-cooling as effective as possible a position dependent magnetic field is applied to the atoms in order to keep the slowing atoms in resonance with the Doppler shifted laser frequency. Such a device is called a **Zeeman slower**.

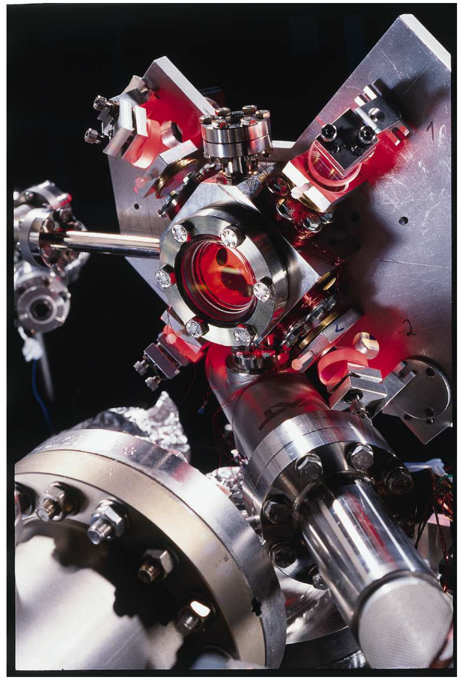
Typical experimental setup...

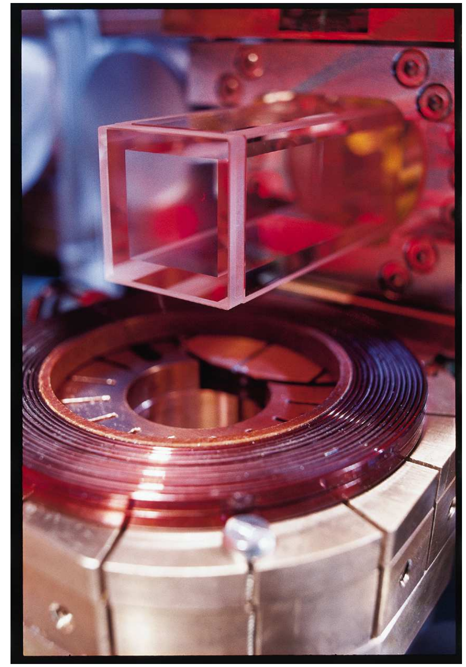
- After the Zeeman slower atoms can be trapped in a magneto optical trap (MOT). Here they are not only trapped, but the same laser beams which are used to trap them (with the help of magnetic fields) cool them them to temperatures in the range of $100\,\mu\mathrm{K}$.
- Atoms have now become cold enough to be trapped by the magnetic trap and after a sufficiently large number of atoms (10^{10}) have accumulated in the MOT, laser beams are turned off. Atoms are then trapped by a purely magnetic trap.

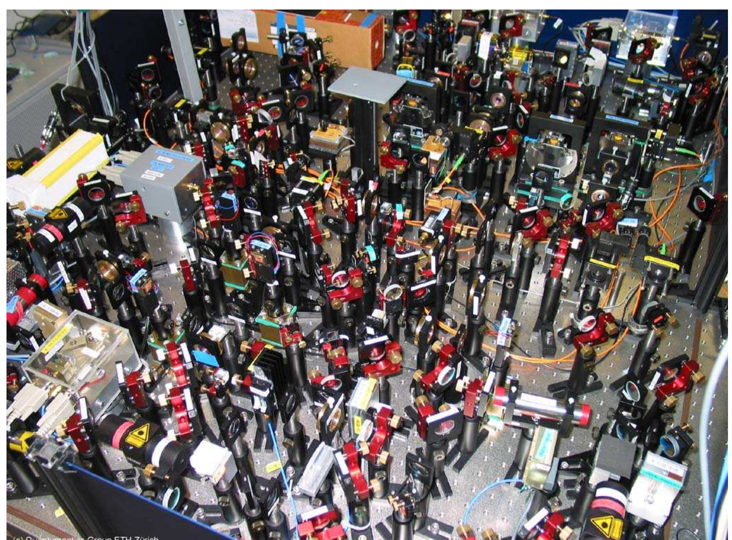
Typical experimental setup...

- To lower the temperature all the way to quantum degeneracy, atoms are now evaporatively cooled. If all goes well, we reach a Bose-Einstein condensate of perhaps 10^6 atoms.
- Next we manipulate the BEC in what ever way we like and investigate its properties. When we image it, we might want to turn off the magnetic trap and allow the BEC to expand to larger size. Then we shine a laser on the BEC and record the resulting picture with the CCD camera. (destructive or non-distructive)
- Repeat the above steps to do the next experiment.
- Do it yourself: http://www.colorado.edu/physics/2000/applets/bec.html

Some pictures of the reality







(Note: that is not a place for storing spare parts)

Exercise and next lecture

- Exercise: Why are you here? What do you expect/wish to learn?
- Next week: Ideal Bose-Einstein condensate in a harmonic trap